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Application of Probable Maximum Precipitation Estimates - United States East of the 105th Meridian

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APPLICATION OF PROBABLE MAXIMUM PRECIPITATION ESTIMATES – UNITED STATES EAST OF THE 105TH MERIDIAN

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ABSTRACT--This study provides a stepwise approach to the temporal and spatial distribution of probable maximum precipitation (PMP) estimates derived from Hydrometeorological Report No. 51, "Probable Maximum Precipitation Estimates - United States East of the 105th Meridian." Included are discussions of the shape and orientation of isohyetal patterns for major rainfalls of record. An elliptical isohyetal pattern with a ratio of major to minor axes of 2.5 to 1 is recommended, and a procedure is outlined for obtaining appropriate isohyet values. A procedure is given to determine PMP values for durations less than 6 hours. Example applications have been worked through to serve as guidance in the use of this procedure.

1. INTRODUCTION

1.1 Background

Generalized estimates of all-season probable maximum precipitation (PMP) applicable to drainages of the United States east of the 105th meridian are provided in Hydrometeorological Report No. 51 (Schreiner and Riedel 1978). Hereinafter, that report will be referred to as HMR No. 51, and references to other reports in this series will be similarly abbreviated.

The terminology in HMR No. 51 has not always been precise, particularly where PMP estimates are referred to as being for drainages from 10 to 20,000 mi^2. It is important to realize that the term drainages as used in that report is a rather loose interpretation when the more precise term is areas. The term drainage or drainage area in the present report will apply to a specific drainage only. HMR No. 51 provides storm-area PMP estimates for a specific range of area sizes (10 to 20,000 mi^2) and durations (6 to 72 hr).

1.2 Objective

The objective of this report is to aid the user in adapting or applying PMP estimates from HMR No. 51 to a specific drainage. This report recommends a procedure for the application of PMP estimates to a drainage for which both the temporal and spatial distributions are needed. This information is necessary for the determination of peak discharge and can be useful in estimating the maximum volume in evaluations of the probable maximum flood (PMF).

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1.3 Definitions

Probable Maximum Precipitation (PMP). Theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year. (This definition is a 1982 revision to that used previously (American Meteorological Society 1959) and results from mutual agreement among the National Weather Service, the U.S. Army Corps of Engineers, and the Bureau of Reclamation.)

PMP Storm Pattern. The isohyetal pattern that encloses the PMP area plus the isohyets of residual precipitation outside the PMP portion of the pattern.

Storm-centered area-averaged PMP. The values obtained from HMR No. 51 corresponding to the area of the PMP portion of the PMP storm pattern. In this report all references to PMP estimates or to incremental PMP infer storm-area averaged PMP.

Drainage-averaged PMP. After the PMP storm pattern has been distributed across a specific drainage and the computational procedure of this report applied, we obtain drainage-averaged PMP estimates. These values include that portion of the PMP storm pattern that occur over the drainage, both PMP and residual.

Temporal Distribution. The order in which 6-hr incremental amounts are arranged in a 3-day sequence (72 hr). This report includes information regarding determination of hourly and smaller units within the maximum 6-hr increment, but does not discuss the distribution of units less than 6-hr.

Spatial Distribution. The value of fixed isohyets in the idealized pattern storm for each 6-hr increment and shorter durations within the maximum 6-hr increment of PMP when area-averaged PMP is to be distributed.

Total Storm Area and Total Storm Distribution. The largest area size and longest duration for which depth-area-duration data are available in the records of major storm rainfall.

Standard Areas. The specific area sizes for which PMP estimates are available from the generalized maps in HMR No. 51, i.e., 10-, 200-, 1,000-, 5,000-, 10,000-, and 20,000-mi^2 areas.

Standard Isohyet Area Sizes. In this report, the standard isohyet area sizes are are those enclosed by the isohyets of the recommended pattern, i.e., 10, 25, 50, 100, 175, 300, 450, 700, 1,000, 1,500, 2,150, 3,000, 4,500, 6,500, 10,000, 15,000, 25,000, 40,000, and 60,000 mi^2.

Residual Precipitation. The precipitation that occurs outside the area of the PMP pattern placed on the drainage, regardless of the area size of the drainage. Because of the irregular shape of the drainage, or because of the choice of a PMP pattern smaller in area than the area of the drainage, the residual precipitation can fall within the drainage. A particular advantage in the consideration of residual precipitation, is that of allowing for the determination of concurrent precipitation, i.e., the precipitation falling on an adjacent drainage as compared to that for which the PMP pattern has been applied.

Isohyetal Orientation. The orientation (direction from north) of the major axis through the elliptical pattern of PMP. The term is used in this study also to define the orientation of precipitation patterns of major storms when approximated by elliptical patterns of best fit.

Within/Without-Storm Depth-Area Relations. This relation evolves from the concept that the depth-area relation for area-averaged PMP represents an envelopment of maximized rainfall from various storms each effective for a different area size(s). The within-storm depth-area relation represents the areal variation of precipitation within a storm that gives PMP for a particular area size. This can also be stated as the storm that results in PMP for one area size may not give PMP for any other area size. Except for the area size that gives PMP, the within-storm depth-area relation will give depths less than PMP for smaller area sizes. This concept is illustrated in the schematic diagram shown in figure 1. In this figure, precipitation for areas in the PMP storm outside the area size of the PMP pattern describes a without-storm depth-area relation. The precipitation described by the without-storm relations is the residual precipitation defined elsewhere in this report.

1.4 Summary of Procedures and Methods of this Report

All procedures described in this study are based on information derived from major storms of record, and are applicable to nonorographic regions of the eastern United States.

The temporal distributions provided allow some flexibility in determining the hydrologically most critical sequence of incremental PMP. The procedure used to determine the temporal distributions has been used in some other Hydrometeorological Branch reports (Riedel 1973, and Schwarz 1973 for example), and is described in chapter 2.

We have surveyed major storm isohyetal patterns for statistics on pattern shape, and have adopted an elliptical shape having a 2.5 to 1 ratio of major to minor axes as representative of a precipitation pattern. This elliptical shape has been adopted for PMP and is applied to all 6-hr incremental patterns. The discussion of the shape of the isohyetal patterns is found in chapter 3.

Another aspect of this study is a generalized approach to adjustments for pattern orientation to fit the drainage when inconsistent with the orientation determined for the PMP isohyetal pattern. Outlined in chapter 4 is an empirical method that allows up to 15 percent reduction to storm-centered area-averaged PMP for drainage areas larger than 3,000 mi^2 which differ by more than 40 degrees from the orientation consistent with PMP-producing storms.

In determining spatial distribution a basic assumption is that rainfall depths for areas smaller and larger than the total area for which PMP is needed over a particular drainage, are less than PMP. (See within/without-storm depth-area definitions.) This assumption, for areas smaller than the PMP, has been commonly made in some other studies by this branch (Riedel 1973, Riedel, et al. 1969, and others), and results in what has been referred to in those reports as within-storm or within-drainage depth-area-duration (D.A.D) relations. Application of a similar assumption to areas larger than that for the PMP is a consideration unique to the present study and introduces the concept of residual precipitation.

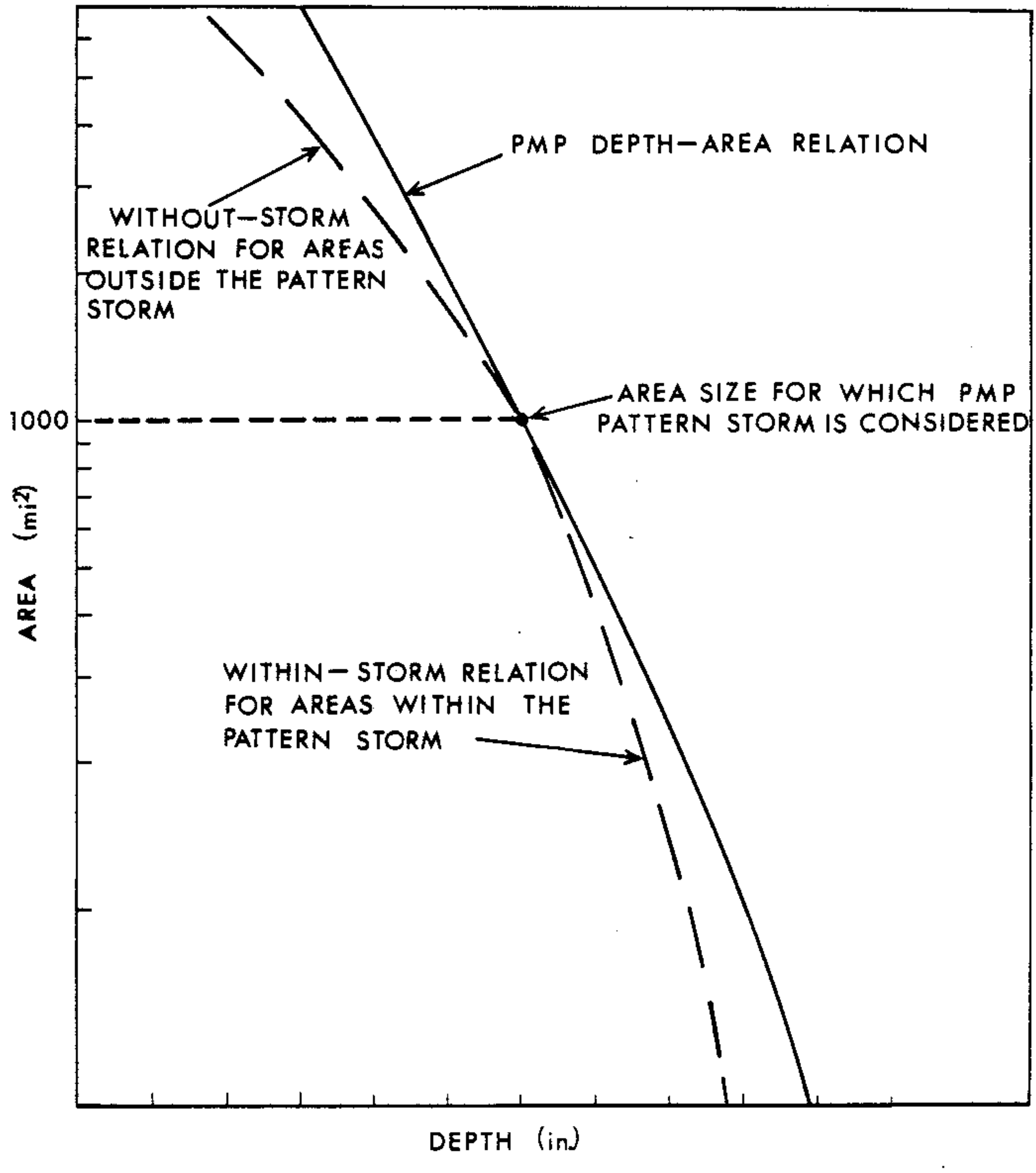


Figure 1.—Schematic diagram showing the relation between depth-area curve for PMP and the within/without-storm relations for PMP at 1,000 mi^2.

(See sec. 1.3 definitions.) Discussion of the procedure to obtain the spatial distribution of PMP and the residual precipitation is given in chapter 5.

For many drainages, it is frequently necessary to have values for durations less than 6 hours. Procedures for obtaining the percentage of the greatest 6-hr increment that occurs in the maximum 5, 15, 30 and 60 min are provided in chapter 6. We do not in this report attempt to define the temporal distribution within the greatest 6-hr increment except to suggest that the 5-, 15- and 30-min values should be included within the maximum 60 min. It is anticipated that the time of occurrence of the maximum 60 min within the 6-hr increment will be the subject of a future study.

1.5 Application to PMP

For those interested in the application of PMP from HMR No. 51 (nonorographic region only) to a specific drainage, chapter 7 is most important. This chapter provides a step-by-step approach to guide the user through the application of procedures developed in this report. Examples have been worked out in sufficient detail to clarify important aspects of these procedures.

The examples in chapter 7 give the user a procedure to obtain the maximum volume of rainfall for a drainage. Finding the maximum volume of rainfall is only part of the hydrologic problem. Another important question is the probable maximum peak flow that could occur at the proposed hydrologic structure. The solution is somewhat more difficult to directly ascertain than finding the maximum volume. The calculation of peak flow is highly dependent on a mixture of basin parameters such as lag time, time of concentration, travel time, and loss rate functions in combination with the amount, distribution and placement of the PMP storm within the drainage. Because of the interaction of these parameters, we cannot provide a simple stepwise procedure to determine peak flow. The user must weigh carefully the effect of the various parameters, drawing on his experience and knowledge of the drainage under study, and determine, through a series of trials, what combination of hydrologic parameters will produce the maximum peak flow.

1.6 Some Other Aspects of Temporal and Spatial Distributions

Although we present a procedure that leads to temporal and spatial distribution of PMP, we recognize that some considerations have not been discussed in this study. When storm data become sufficiently plentiful, and when our knowledge of storm dynamics permits, these considerations may lead to improvements in the current procedures. Meanwhile only brief comments follow regarding two such considerations for future study.

1.6.1 Moving rainfall centers

Our procedure assumes that isohyetal patterns for all 6-hr PMP increments remain fixed with time, i.e., all are centered at the same location. For large drainages (greater than 10,000 mi^2, for example), it is meteorologically reasonable for the rainfall center to travel across the drainage with time during the storm. It is conceivable that such movement could result in a higher flood peak if the direction and speed of movement coincides with downstream progression of the flood crest.

It was decided jointly by the Corps of Engineers and the Hydrometeorological Branch that the present report would not cover application of moving centers. Generalization of moving centers would require analysis of observational data such as incremental storm isohyetal patterns that are presently not available. It is anticipated that a future study will cover moving centers.

1.6.2 Distributions from an actual storm

Use of elliptical patterns for spatial distribution permits simplicity in generalized depth-area relations and in determining isohyet values. It also helps maintain consistency in results among drainages, area sizes, and durations. Such consistency is also maintained by the recommended temporal distributions. An alternate but unrecommended procedure is to adopt the distributions of a record storm precipitation that occurred on the drainage or within a homogeneous region including the drainage.

The isohyetal pattern from an actual storm might "fit" a drainage better than an elliptical pattern, and multiplying the isohyets by percent of PMP (say for 6 hours for the drainage, divided by the drainage depth from the storm pattern after it is located on the drainage) will give isohyet values for PMP. Such isohyets, however, quite possibly could give greater than PMP depths for smaller areas within the drainage.

The temporal distribution of such a storm could also be used for PMP. Again, however, there could very likely be problems. The most intense three 6-hr rain increments in a 72-hr storm may be widely separated in a time sequence of incremental rainfall (mass curve). Thus, 12- or 18-hr PMP could not be obtained unless rain bursts somehow were brought together. However, such arrangement is often done as a maximization step and PMP depths from HMR No. 51 used. These modifications would be towards the generalized criteria of the present study in which there are no results that are inconsistent or irreconcilable.

Paulhus and Gilman (1953) published a technique for using an actual pattern for distributing PMP. The referenced paper describes a "sliding" technique for obtaining the spatial distribution of PMP that has its greatest merit in applications in the more orographic regions (stippled zones in HMR No. 51) covered by this study, such as the Appalachians and along the western border to the region, where site-specific studies are recommended. However, we advise caution in application of this technique directly as Paulhus and Gilman have proposed, in that it is possible to obtain PMP for a much smaller area size than that for the drainage to which it is applied. Since this disagrees with our within-storm concept, we therefore suggest adherence to the following modifications to the technique presented by Paulhus and Gilman, if it is used:

a. Use a set of depth-area relations (from HMR No. 51) which, when "slid over" the depth-area relations for the storm, will give PMP for an area size within 10 percent of the area of the drainage of concern.

b. It is desirable that PMP (from HMR No. 51) be obtained for at least the hydrologically critical duration.

c. For other durations between 6 and 72 hours, stay within 15 percent of PMP as specified in HMR No. 51. For additional information regarding application of this technique, the reader is referred to the Paulhus and Gilman paper.

1.7 Other Meteorological Considerations

Other aspects of extreme rainfall criteria can be important to determinations of peak flow. Some of these aspects are described here.

1.7.1 PMP for smaller areas within the total drainage.

Our previous studies have concentrated on defining PMP for the total drainage area. In fact, in the present study we recommend spatial distributions resulting in somewhat less than PMP for smaller as well as larger areas than the PMP pattern. The question can naturally be asked, does PMP for a smaller area size than the storm area size that is applicable to the entire drainage, which when centered over a portion of the drainage (experiencing more intense rainfall than that for the entire drainage), result in a more critical peak flow? There is a possibility that PMP covering only a subportion of the drainage could provide a hydrologically more critical peak discharge, and the hydrologist should consider such a possibility. The depth of rainfall to use over the remaining portion of the drainage would need to be specified. (See discussion on residual precipitation in sections 3.5.3 and 5.2.5.)

1.7.2 Rains for extended periods

Especially for large drainages, rainfalls for durations longer than 3 days could be important in defining critical volumes for hydrologic design. As examples, the Hydrometeorological Branch, working with Corps of Engineers hydrologists, has evaluated the meteorology of hypothetical sequences of record storms transposed in space and recommended how close together such storms can follow each other (Myers 1959, and Schwarz 1961). Similar studies may be needed for other large drainage projects. Sufficiently severe assumptions, however, relative to how full reservoirs are prior to the PMF and the antecedent soil conditions, could obviate the need for such studies.

1.8 Report Preparation

Preparation of this report began in 1977 as follow on studies to HMR No. 51. Initial discussions with the Corps of Engineers outlined the scope of the project. As indicated in a previous section, certain problems were left to be considered in later studies. The basic studies were undertaken when all the authors were affiliated with the National Weather Service (NWS). These studies were completed after one of the authors, L. Schreiner, transferred to the Bureau of Reclamation (USBR). Several of the concepts and procedures included in this report evolved after Mr. Schreiner's transfer, as a collaborative effort of the three authors and other meteorologists affiliated with both the NWS and the USBR.

2. TEMPORAL DISTRIBUTION

2.1 Introduction

When applying PMP to determine the flood hydrograph, it is necessary to specify how the rain falls with time, that is, in what order various rain increments are arranged with time from the beginning of the storm. Such a rainfall sequence in an actual storm is given by what is called a mass curve of rainfall, or the accumulated rainfall plotted against time from the storm beginning. Mass curves observed in severe storms show a great variety of sequences of rain increments.

Table 1.--Major storms from HMR No. 51 used in this study

Storm center location	Date	Storm assignment number	Lat. (°)	Lat. (')	Long. (°)	Long. (')	Total storm duration (hr)	Total storm area size (mi^2)	Orient. of pattern (°)
1. Jefferson, OH (T)#	9/10-13/1878	OR 9-19	41	45	80	46	84	90,000	190
2. Wellsboro, PA	5/30-6/1/1889	SA 1-1	41	45	77	17	60	82,000	200
3. Greeley, NE	6/4-7/1896	MR 4-3	41	33	98	32	78	84,000	205
4. Lambert, MN	7/18-22/1897	UMV 1-2	47	47	95	55	102	80,000	230
5. Jewell, MD	7/26-29/1897	NA 1-7B	38	46	76	34	96	32,000	205
6. Hearne, TX (T)	6/27-7/1/1899	GM 3-4	30	52	96	37	108	78,000	170
7. Eutaw, AL	4/15-18/00	LMV 2-5	32	47	87	50	84	75,000	230
8. Paterson, NJ (T)	10/7-11/03	GL 4-9	40	55	74	10	96	35,000	170
9. Medford, WI	6/3-8/05	GL 2-12	45	08	90	20	120	67,000	205
10. Bonaparte, IA	6/9-10/05	UMV 2-5	40	42	91	48	12	20,000	285
11. Warrick, MT	6/6-8/06	MR 5-13	48	04	109	39	54	40,000	250
12. Knickerbocker, TX	8/4-6/06	GM 3-14	31	17	100	48	48	24,600	235
13. Meeker, OK	10/19-24/08	SW 1-11	35	30	96	54	126	80,000	200
14. Beaulieu, MN	7/18-23/09	UMV 1-11A	47	21	95	48	108	5,000	285
15. Merryville, LA	3/24-28/14	LMV 3-19	30	46	93	32	96	125,000	200
16. Cooper, MI	8/31-9/1/14	GL 2-16	42	25	85	35	6	1,200	300
17. Altapass, NC (T)	7/15-17/16	SA 2-9	35	53	82	01	108	37,000	155
18. Meek, NM (T)	9/15-17/19	GM 5-15B	33	41	105	11	54	75,000	200
19. Springbrook, MT	6/17-21/21	MR 4-21	47	18	105	35	108	52,600	240
20. Thrall, TX (T)	9/8-10/21	GM 4-12	30	35	97	18	48	12,500	210
21. Savageton, WY	9/27-10/1/23	MR 4-23	43	52	105	47	108	95,000	230
22. Boyden, IA	9/17-19/26	MR 4-24	43	12	96	00	54	63,000	240
23. Kinsman Notch, NH (T)	11/2-4/27	NA 1-17	44	03	71	45	60	60,000	220
24. Elba, AL	3/11-16/29	LMV 2-20	31	25	86	04	114	100,000	250
25. St. Fish Htchy., TX	6/30-7/2/32	GM 5-1	30	10	99	21	42	30,000	205
26. Scituate, RI (T)	9/16-17/32	NA 1-20A	41	47	71	30	48	10,000	200
27. Ripogenus Dam, ME (T)	9/16-17/32	NA 1-20B	45	53	69	15	30	10,000	200
28. Cheyenne, OK	4/3-4/34	SW 2-11	35	37	99	40	18	2,200	230
29. Simmesport, LA	5/16-20/35	LMV 4-21	30	59	91	48	102	75,000	235
30. Hale , CO	5/30-31/35	MR 3-28A	39	36	102	08	24	6,300*	235

Table 1.—Major storms from HMR No. 51 used in this study - Continued

	Storm center location	Date	Storm assignment number	Lat. (°)	Lat. (')	Long. (°)	Long. (')	Total storm duration (hr)	Total storm area size (mi²)	Orient. of pattern (°)
31.	Woodward Rch., TX	5/31/35	GM 5-20	29	20	99	18	10	7,000	210
32.	Hector, NY	7/6-10/35	NA 1-27	42	30	76	53	90	38,500	255
33.	Snyder, TX	6/19-20/39	--	32	44	100	55	6	2,000	285
34.	Grant Twnshp., NE	6/3-4/40	MR 4-5	42	01	96	53	20	20,000	210
35.	Ewan, NJ (T)	9/1/40	NA 2-4	39	42	75	12	12	2,000	205
36.	Hallett, OK	9/2-6/40	SW 2-18	36	15	96	36	90	20,000	160
37.	Hayward, WI	8/28-31/41	UMV 1-22	46	00	91	28	78	60,000	270
38.	Smethport, PA	7/17-18/42	OR 9-23	41	50	78	25	24	4,300	145
39.	Big Meadows, VA (T)	10/11-17/42	SA 1-28A	38	31	78	26	156	25,000	200
40.	Warner, OK	5/6-12/43	SW 2-20	35	29	95	18	144	212,000	225
41.	Stanton, NE	6/10-13/44	MR 6-15	41	52	97	03	78	16,000	260
42.	Collinsville, IL	8/12-16/46	MR 7-2B	38	40	89	59	114	20,400	260
43.	Del Rio, TX	6/23-24/48	--	29	22	100	37	<24	10,000	180
44.	Yankeetown, FL (T)	9/3-7/50	SA 5-8	29	03	82	42	96	43,500	205
45.	Council Grove, KS	7/9-13/51	MR 10-2	38	40	96	30	108	57,000	280
46.	Ritter, IA	6/7/53	MR 10-8	43	15	95	48	20	10,000	220
47.	Vic Pierce, TX (T)	6/23-28/54	SW 3-22	30	22	101	23	120	27,900	140
48.	Bolton, Ont., Can. (T)	10/14-15/54	ONT 10-54	43	52	79	48	78	20,000	190
49.	Westfield, MA (T)	8/17-20/55	NA 2-22A	42	07	72	45	72	35,000	230
50.	St. Pierre Baptiste, Que., Can.	8/3-4/57	QUE 8-57	46	12	71	35	18	7,000	285
51.	Sombreretillo, Mex. (T)	9/19-24/67	SW 3-24	26	18	99	55	126	60,000	220
52.	Tyro, VA (T)	8/19-20/69	NA 2-23	37	49	79	00	48	15,000	270
53.	Zerbe, PA (T)	6/19-23/72	NA 2-24A	40	37	76	32	96	130,000	200

#(T) = Precipitation associated with tropical cyclone
* = Area of combined centers of precipitation with Elbert, CO 39°13'N, 104°32'W, generally referred to as Cherry Ck.

Certain sequences result in more critical flow (higher peak) than others. We leave the determination of criticality to the hydrologist, but recognize that the mass curve or temporal distribution selected for PMP is important.

PMP estimates can be obtained in HMR No. 51 for 6-, 12-, 24-, 48- and 72-hr durations. A plot of these depths against duration joined by a smooth curve defines PMP for all durations between 6 and 72 hours. In many applications, definition of PMP by 6-hr time increments is sufficient. Thus, PMP values for 6, 12, 18, 24, ..., 72 hr can be read from such a smooth curve. Successive subtraction of the PMP for each of these durations from that of the duration 6-hr longer gives 6-hr increments of PMP. We have shown in HMR No. 51 that, in general, allowing PMP for all durations (6 to 72 hr) to occur in a single storm is not an undue maximization.

2.2 Observed Sequences of 6-hr Increments in Major Storms

We considered the sequences of 6-hr rain increments of the more important storms east of the 105th meridian as guidance for recommending sequences for PMP. These storms, 53 of which are given in the appendix of HMR No. 51, are listed in table 1 and represent a primary data base for this study. Table 1 includes information on storm location, duration, areal extent, and the orientation of the isohyetal pattern (refer to chapter 4).

To obtain information on the chronological sequence of 6-hr increments of precipitation, we referred to storm data summarized for most major storms listed in table 1 (not available for the 2 storms of 9/16-17/1932, and those of 6/19-20/1939, 6/23-24/1948, 10/14-15/1954, and 8/3-4/1957). For the 47 remaining storms, these data are contained in what we refer to as Part 2 storm study files in which point data are grouped to obtain chronological sequences of areally averaged depths. A search was made through these storms for cases in which depths were given for both 100- and 10,000-mi^2 approximate areas for the storm center with maximum precipitation. The storms were further limited to those for which 6-hr incremental depths occurred over a period of more than 48 hr, to assure us that we were considering representative 3-day storms.

Table 2 lists the 28 storms that met these conditions, and separates them by storm type--tropical and nontropical. The remaining 19 storms had rainfall durations or areas that failed to meet our threshold. It should be pointed out that the limitations for 48-hr sequences from the Part 2 data do not necessarily agree with the listing of total-storm duration given in table 1. For example, the Greeley, Nebraska (6/4-7/1896) storm in table 1 is considered to have a total storm duration of 78 hr (U.S. Army Corps of Engineers 1945-). This same storm for the 100- and 10,000-mi^2 approximate areas in the maximum storm rainfall center provides sequences of depths only up to about 24 hr ($\sim$100 mi^2) and 36-hr ($\sim$10,000 mi^2).

A rainfall was considered tropical if it occurred within 200 miles of a storm track contained in Neumann, et al. (1978), and if the rain occurred within 2 days prior to passage of the storm. Other storm rainfalls were also designated tropical if they occurred within 500 miles beyond and within 2 days after the last reported position of a tropical cyclone track in Neumann. In such cases, the assumption made was that moisture from the tropical cyclone continued to move

Table 2.—Major storms from table 1 used in study of temporal distributions

Location	Date	Storm assignment number
TROPICAL		
Jefferson, OH	9/10-13/1878	OR 9-19
Hearne, TX	6/27-7/1/1899	GM 3-4
Paterson, NJ	10/7-11/1903	GL 4-9
Altapass, NC	7/15-17/1916	SA 2-9
Big Meadows, VA	10/11-17/1942	SA 1-28A
Yankeetown, FL	9/3-7/1950	SA 5-8
Vic Pierce, TX	6/23-28/1954	SW 3-22
Westfield, MA	8/17-20/1955	NA 2-22A
Sombreretillo, Mex.	9/19-24/1967	SW 3-24
Zerbe, PA	6/19-23/1972	NA 2-24A
NONTROPICAL		
Lambert, MN	7/18-22/1897	UMV 1-2
Jewell, MD	7/26-29/1897	NA 1-7B
Eutaw, AL	4/15-18/1900	LMV 2-5
Medford, WI	6/3-8/1905	GL 2-12
Warrick, MT	6/6-8/1906	MR 5-13
Meeker, OK	10/19-24/1908	SW 1-11
Merryville, LA	3/24-28/1914	LMV 3-19
Springbrook, MT	6/17-21/1921	MR 4-21
Thrall, TX	9/8-10/1921	GM 4-12
Savageton, WY	9/27-10/1/1923	MR 4-23
Elba, AL	3/11-16/1929	LMV 2-20
Simmesport, LA	5/16-20/1935	LMV 4-21
Hector, NY	7/6-10/1935	NA 1-27
Hayward, WI	8/28-31/1941	UMV 1-22
Warner, OK	5/6-12/1943	SW 2-20
Stanton, NE	6/10-13/1944	MR 6-15
Collinsville, IL	8/12-16/1946	MR 7-2B
Council Grove, KS	7/9-13/1951	MR 10-2

beyond the dissipated circulation system and possibly combined with frontal or orographic mechanisms to produce the observed extreme rain. Such probably was the case with the Big Meadows, Virginia (10/11-17/1942) rain listed in table 2. A further check was made of daily weather maps to determine if any of these rains may have been associated with tropical disturbances of less intensity than covered in Neumann, et al. The Hearne, Texas (6/27-7/1/1899) rain, as an important example, is believed to have resulted from extreme moisture associated with one of these weaker systems located off the Texas Gulf Coast, and which moved rapidly inland. More discussion on meteorological factors in extreme rainfalls is given in chapter 4.

While the sample of storms in table 2 is too small to set quantitative differences, we wish to see if qualitative differences appear. Figure 2, as an example, shows sequences of 6-hr increments for 5 of the storms in table 2. (Two of the five are tropical.) In this figure, the 100-mi^2 results are shown as solid lines and the 10,000-mi^2 results as dashed lines. Incremental amounts are expressed as a percentage of the 72-hr rainfall.

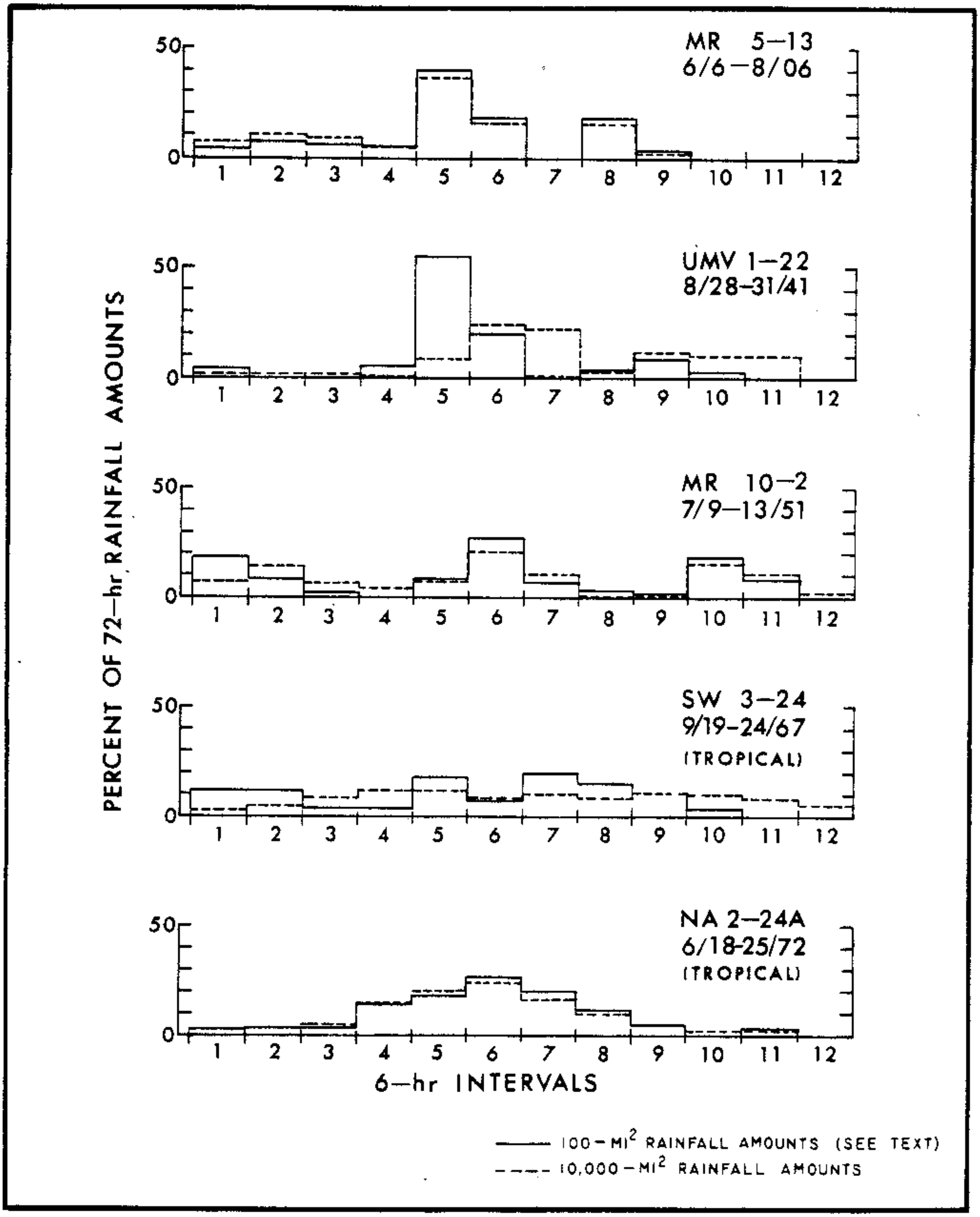


Figure 2.—Examples of temporal sequences of 6-hr precipitation in major storms.

We defined a rain burst as one or more consecutive 6-hr rain increment(s) for which each individual increment has 10 percent or more of the 72-hr rainfall. A second set of results was obtained by redefining a rain burst as 20 percent or more of the 72-hr rainfall.

Examination of the incremental rainfall sequences for each of the 28 storms in table 2 allowed us to compile some constructive information. We tallied the number of bursts in each sequence, the duration of each burst, and the time interval between bursts. Table 3 summarizes this information by area size and storm type for the 28 storms in table 2. (Values in parentheses represent data based on a burst defined as $\geq$ 20 percent of the 72-hr rainfall.) Part (a) summarizes the number of rain bursts in the 72-hr period of maximum rainfall; part (b) the duration (in hours) of the rain bursts; and part (c) the number of hours between bursts.

The first example in figure 2 for the storm of June 6-8, 1906, is used to illustrate these three temporal characteristics. There are two bursts observed for the 100-mi^2 area and 3 bursts for the 10,000-mi^2 area. These counts went into part (a) of table 3. For 100 mi^2, the first rain burst is 12 hr long and the second is 6 hr long. These are separated by 6 hr. The first burst for 10,000 mi^2 is 6 hr long separated by 12 hr from the second burst of 12 hr, which is separated by 6 hr from the last burst of 6 hr. These values are included in parts (b) and (c) of table 3. Some conclusions drawn from the summaries in table 3 are the following:

1. In part (a), fewer rain bursts are observed when the 20 percent threshold is applied than with the 10 percent threshold.

2. For the 10 percent threshold, a larger fraction of tropical storms (8/10 at 100 mi^2 and 6/10 at 10,000 mi^2) tends to have single bursts in a 72-hr period than do nontropical storms (6/18 at 100 mi^2 and 6/18 at 10,000 mi^2). This is indicative of the greater occurrence of short-duration thunderstorms which cause multiple bursts in nontropical storms. However, when a rain burst is defined as 20 percent or greater of the 72-hr total rainfall, the tendency is to lessen the difference between storm types (6/10 vs. 14/18 at 100 mi^2 and 6/10 vs. 13/18 at 10,000 mi^2).

3. Rain burst lengths between 6 and 24 hr dominate for both area sizes and storm types (part (b)). There appears to be a significant difference between storm type and the length of rain bursts, based on this limited sample. Nontropical storms show notably shorter-duration bursts (89 percent are 12 hr or less) than do tropical storms (77 percent are 12 hr or less).

4. The number of hours between rain bursts in tropical storms typically is about 6 to 12 hr, while nontropical storms showed intervals between 6 and 30 hr (part (c)).

Table 3.—Summary of rain burst characteristics of 28 major rainfalls listed in table 2

Part (a); Number of bursts

	Number of rain bursts in a 72-hr period								Total	
	0		1		2		3			
Area (mi^2)	T	NT	T	NT	T	NT	T	NT	T	NT
	Number of Storms									
100	0(2)	0(0)	8(6)	6(14)	0(2)	7(4)	2(0)	5(0)	10	18
10,000	0(4)	0(1)	6(6)	6(13)	3(0)	7(4)	1(0)	5(0)	10	18

Part (b); Duration of bursts

	Duration of rain bursts (hr)												Total	
	6		12		18		24		30		36			
Area (mi^2)	T	NT	T	NT	T	NT	T	NT	T	NT	T	NT	T	NT
	Number of bursts													
100	3(7)	19(14)	3(3)	12(8)	3(0)	4(0)	3(0)	0(0)	2(0)	0(0)	0(0)	0(0)	14(10)	35(22)
10,000	3(2)	14(14)	5(3)	13(7)	0(0)	7(0)	4(1)	0(0)	2(0)	0(0)	1(0)	1(0)	15(6)	35(21)

Part (c); Duration of intervals

	Number of hours between rain bursts (length of intervals)												Total	
	6		12		18		24		30		36			
Area (mi^2)	T	NT	T	NT	T	NT	T	NT	T	NT	T	NT	T	NT
	Number of intervals													
100	2(2)	6(0)	2(0)	5(0)	0(0)	3(3)	0(0)	1(0)	0(0)	2(1)	0(0)	0(0)	4(2)	17(4)
10,000	4(0)	5(1)	1(0)	7(0)	0(0)	4(2)	0(0)	0(0)	0(0)	1(1)	0(0)	0(0)	5(0)	17(4)

T - tropical, NT - nontropical

( ) - Values in parentheses are for results when definition for rain burst is increased from $\geq$ 10% to $\geq$ 20% of the 72-hr total rain (see text).

2.3 Recommended Sequences for PMP Increments

While the 28-storm sample shows some evidence for rain burst sequences to differ depending on the storm type, table 3 suggests the difference may be in part due to the choice of threshold value. Furthermore, differentiation by storm type would necessitate delineating regions of control on PMP. This is not recommended since anomalies in major rains related to storm type occur. An example of this is one of the most extreme rain events for large areas along the gulf coast, the Elba, Alabama storm of 3/11-16/1929. This was a nontropical storm. Another reason for not distinguishing time sequences for PMP by storm type is that the PMP in coastal regions may be produced by a complex weather situation that is a mixture of both tropical and nontropical influences. Therefore, one standard set of temporal sequences, independent of storm type, is recommended for the PMP increments determined as described in section 2.1.

The limited sample of storms in table 2 was further examined for guidance on how to arrange the increments of PMP. Almost any arrangement could be found in these data. The Warner, Oklahoma, (9/6-12/1943) storm showed the six greatest 6-hr increments to be consecutive in the middle of the 72-hr rain sequence, while the Council Grove, Kansas (7/9-13/1951) storm showed daily bursts of 12 hr with lesser rains between.

To get PMP for all durations within a 72-hr storm requires that the 6-hr increments be arranged with a single peak (fig. 3). We chose a 24-hr period as including most rain bursts in major storms, and set this as the length of rain bursts for the PMP, giving three 24-hr periods in a 72-hr period. Based on results from examination of the 28-storm sample, guidance follows for arranging 6-hr increments of PMP within a 72-hr period. To obtain PMP for all durations:

A. Arrange the individual 6-hr increments such that they decrease progressively to either side of the greatest 6-hr increment. This implies that the lowest 6-hr increment will be at either the beginning or the end of the sequence.

B. Place the four greatest 6-hr increments at any position in the sequence except within the first 24-hr period of the storm sequence. Our study of major storms (exeeding 48-hr durations) shows maximum rainfall rarely occurs at the beginning of the sequence.

3. ISOHYETAL PATTERN

3.1 Introduction

There are two important considerations relative to the isohyetal pattern used for PMP rainfalls. The first is the shape of the pattern and how it is to be represented. The second is the number and magnitude of isohyets within the pattern.

This chapter deals with the selection of the pattern shape and the number of isohyets considered to represent the shape. The magnitude of the individual isohyets will be determined from the procedure described in chapter 5, Isohyet Values. In addition to establishing the shape of the isohyetal pattern for

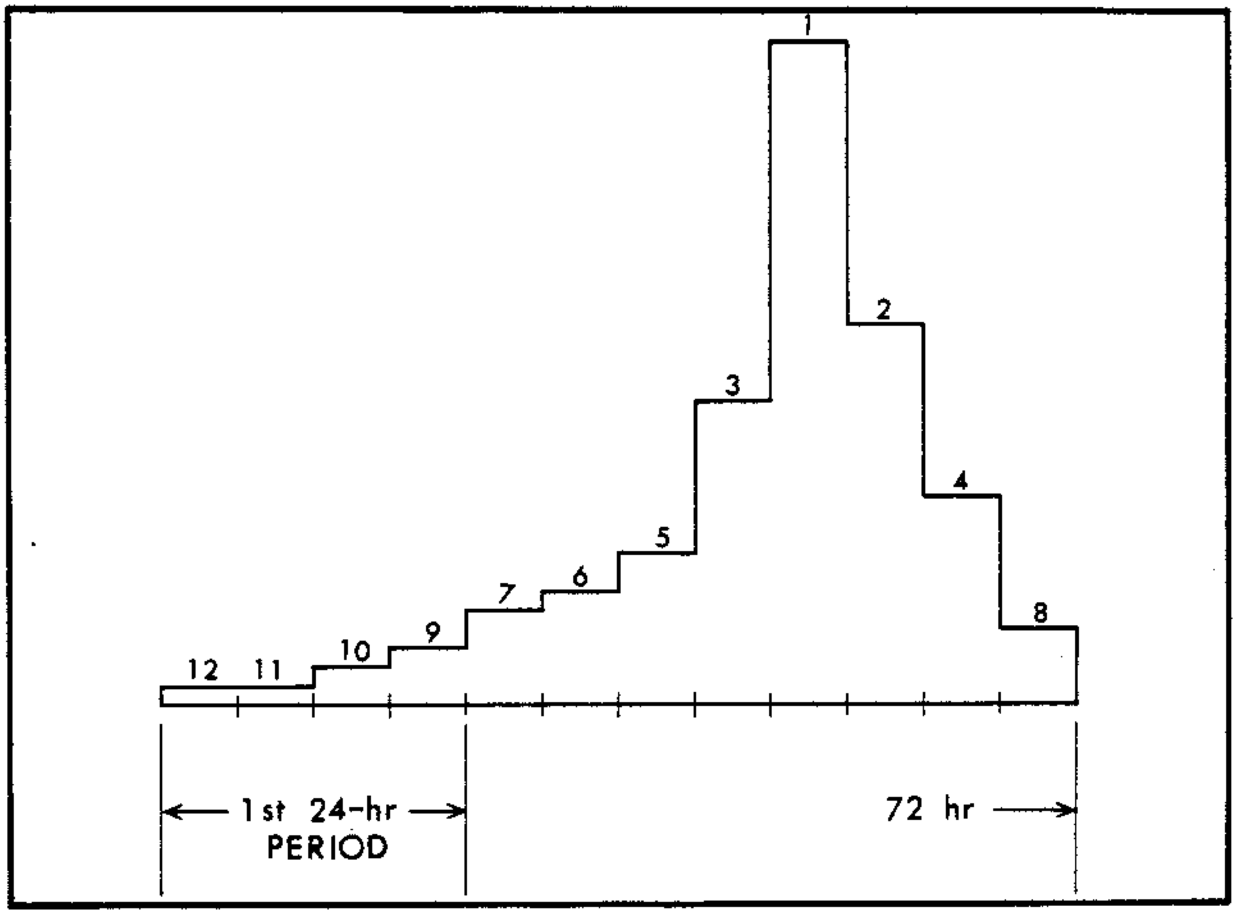


Figure 3.—Schematic example of one temporal sequence allowed for 6-hr increments of PMP. See text for restrictions placed on allowed sequences.

distributing area-averaged PMP over a drainage for the three greatest increments, it should be emphasized that this shape applies as well to the remaining 6-hr increments of PMP for distribution of residual precipitation and other adjustments.

3.2 Isohyetal Shape

To understand more about the shape of isohyetal patterns, we considered those for the 53 major rainfalls listed in table 1. It was apparent from this sample of storms as well as from our experience with other samples that the most representative shape for all such storms is that of an ellipse. Actual storm patterns in general are extended in one or more directions, primarily as a result of storm movement, and one finds that an ellipse having a particular ratio of major to minor axis can be fit to the portion of heaviest precipitation in most storms. Therefore, one question we posed was, what was the most representative ratio of axes for the major storms in our sample. Also of interest was to learn the variation of pattern shape with area size and with region.

To determine the shape ratio (i.e., the ratio of the major to minor axis) for the storms in our sample, we developed a number of elliptical templates that were scaled to contain 20,000 mi^2, relative to the small isohyetal maps portrayed in "Storm Rainfall in the United States" (U.S. Army Corps of Engineers 1945-), hereafter referred to as "Storm Rainfall." These templates had shape ratios that varied between 1 and 8. For each storm, we chose the template which best fit the shape of the isohyets that enclosed approximately 20,000-mi^2 areas of greatest rainfall. Judgment of fit was necessary, particularly for storms with large areas, or those near coastal zones where only partial isohyetal patterns were available. For those smaller area storms, a shape ratio was determined based on the ratio of major to minor axis measured on the storm isohyetal pattern.

The variation of shape ratios for the 53-storm sample is summarized in table 4. Shape ratios of 2 are most common, followed by those of 3 and 4. Of the storms in table 4, 62 percent had shape ratios of 2 or 3, and 83 percent had shape ratios of 2 to 4.

Table 4.—Shape ratios of isohyetal patterns for 53 major rain events (see table 1)

	Shape Ratio								
	1	2	3	4	5	6	7	8	Total
No. of patterns	2	22	11	11	4	2	1	0	53
% of total	3.8	41.5	20.8	20.8	7.5	3.8	1.9	0	100
Accum. %	4	45	66	87	94	98	100	100	

Before we draw any conclusions from table 4, we wanted to know if there was a variation in shape ratio with region or area size. To check the regional variation of shape ratios, we chose to separate the region into meteorologically homogeneous subregions as shown in figure 4. These subregions were not meant to represent the entire region of homogeneity but to be sufficiently independent portions of such broadscale subregions among which one might expect to find differences in shape ratios. These regions, shown in figure 4, contained 33 (62%) of the 53 storms.

Table 5 shows the distribution of shape ratios within each of the six subregions, and although the number of storms in each is small, the percent of total shown at the bottom of the table is somewhat similar to that for the entire sample given in table 4. The number of storms in table 5 is too small to be significant, but distinguishable regional differences are not apparent, all tending to support shape ratios of 2 or 3.

Table 5.—Shape ratios for six subregions

	Shape Ratio								Total no.
Subregions	1	2	3	4	5	6	7	8	of storms
	% of storms in region								
Atlantic Coast	20	40	0	20	20	0	0	0	5
Appalachians	20	40	20	0	20	0	0	0	5
Gulf Coast	0	56	22	11	11	0	0	0	9
Central Plains	0	67	0	17	17	0	0	0	6
North Plains	0	0	50	0	0	25	25	0	4
Rocky Mt. Slopes	0	50	25	25	0	0	0	0	4
									33
% of total	6	45	18	12	12	3	3	0	99

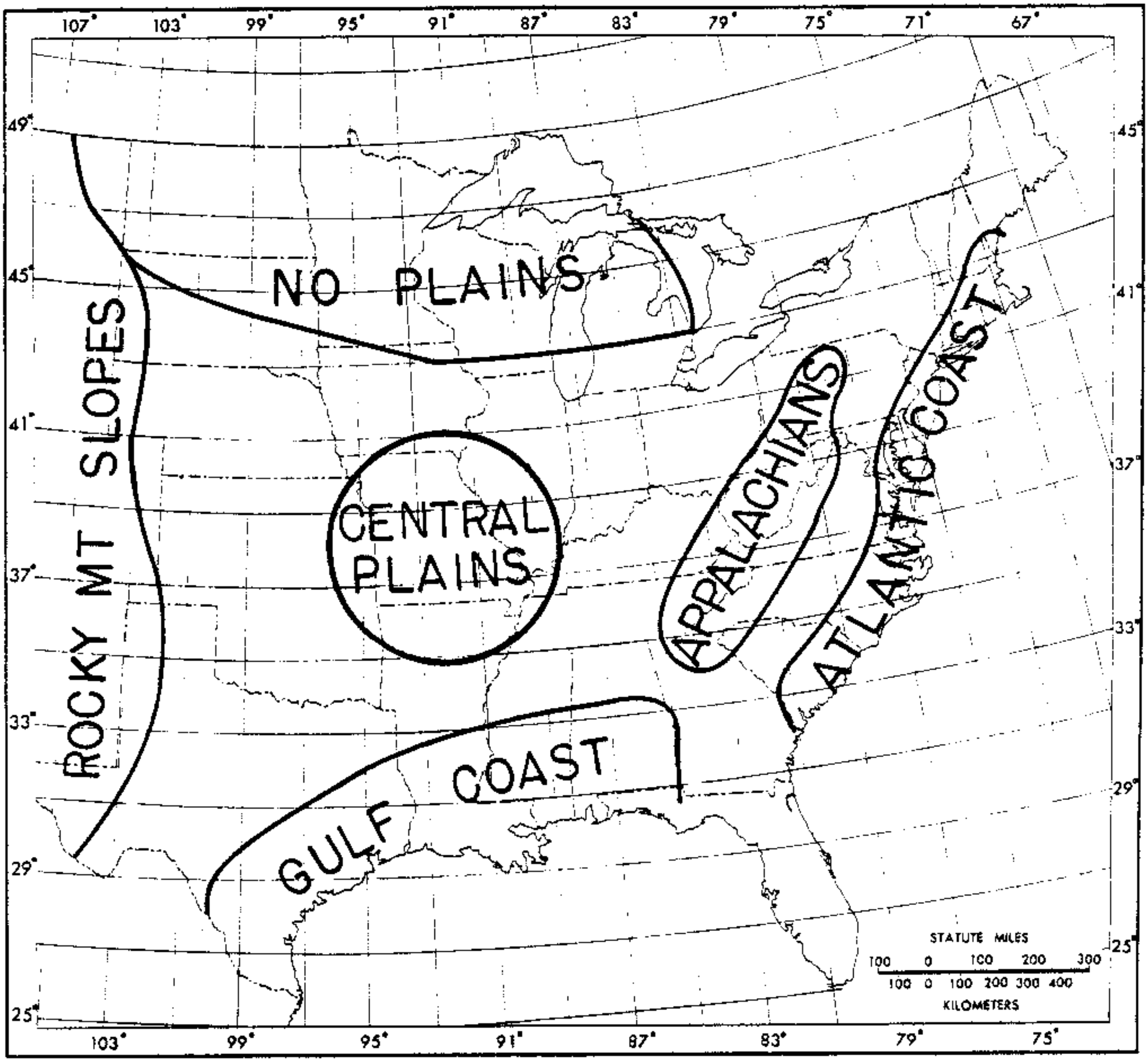


Figure 4.--Homogeneous topographic/climatologic subregions used in study of regional variation of isohyetal patterns.

The appendix contains a discussion of a larger sample of storms, 183 of which occurred in these same six subregions. Results from these storms are shown in table 6. Information from table 6 indicates that the Atlantic Coast and North Plains regions have the greatest percentage (16) of storms with shape ratios greater than 5. The North Plains also has the greatest percentage (16) of approximately circular patterns. The Appalachians show the greatest percentage of storms with shape ratios of 4 and 5. This may be a reflection of an orographic effect of the mountains combined with the northeastward movement of storms along the east coast. These results are not typical of all orographic regions, for shape ratios of 2 predominate on the Rocky Mountain Slopes. This is meteorologically reasonable since many large storms in this region result from nearly stationary weather systems over or near the east face of the mountains.

Table 6.—Shape ratios of 20,000-mi^2 isohyetal patterns for six subregions

Subregions	Shape Ratio 1	2	3	4	5	6	7	8	Total no. of storms
	% of storms in region								
Atlantic Coast	4	31	19	15	15	12	4	0	26
Appalachians	4	17	13	30	30	0	0	4	23
Gulf Coast	6	42	28	10	6	2	2	4	50
Central Plains	2	26	35	16	9	9	0	2	43
North Plains	16	28	28	8	4	8	4	4	25
Rocky Mt. Slopes	6	56	19	0	13	0	0	6	16
% of total subsample	6	33	25	14	12	5	2	3	100 / 183

Although some of the differences are meteorologically reasonable and may in fact represent variations over a regional extent, it must be recognized that the regional samples in table 6 are somewhat small in all but the Gulf Coast and Central Plains. It is difficult to compare the results in tables 5 and 6. Seven storms in table 5 that had particularly small total areas were not included in the sample for table 6. Nevertheless, it was concluded from these tables that there is little apparent regional variation amongst shape ratios.

The variation of shape ratios with area size for the 53 storm sample, regardless of duration, is shown in table 7. Here too the results show no strong variation with area size.

Table 7.—Shape ratios of major isohyetal patterns relative to area size of total storm

Area size (10^3 mi^2)	Shape Ratio 1	2	3	4	5	6	7	8	Total no. of storms
	% of storm in category								
≤0.3									0
0.31 - 5.0	40	20	20	20					5
5.1 - 10.0		67		33					3
10.1 - 20.0		57		28	14				7
20.1 - 30.0	12	50	12	25					8
30.1 - 40.0		50		33	17				6
40.1 - 50.0		50		50					2
50.1 - 70.0		22	33	11		22	11		9
70.1 - 90.0		28	43		28				7
≥ 90.0		33	50	17					6
% of total	6	40	21	21	8	4	2	0	53

In table 7, the larger values in each row have been circled. In this sample, there appears to be a tendency for larger percentages of storms to be circular at the smaller area size. In the same manner, there is a tendency for shape ratios to increase from 2 for areas between 5,000 mi^2 and 50,000 mi^2 to 3 for larger areas. Although these results are perhaps handicapped by the small size of the sample, somewhat similar results were obtained from the larger sample of storms discussed in the appendix.

3.3 Summary of Analysis

The following conclusions were drawn from analysis of shape ratios of major storm isohyetal patterns.

1. Approximately 60 percent of our sample of major storms had shape ratios between 2 and 3.

2. No strong regional variation of shape ratios was apparent, although some meteorologically reasonable trends could be obtained from the data.

3. No strong relation was found between shape ratio and total-storm area size, but there was some evidence that lower shape ratios occur with the smaller area sizes.

3.4 Recommended Isohyetal Pattern for PMP

Since a majority of the storms considered in this study had shape ratios of 2 and 3, we recommend an idealized (elliptical) isohyetal pattern with a ratio of major to minor axis of 2.5 to 1 for distribution of all 6-hr increments of precipitation over drainages in the nonstippled zones east of the 105th meridian (see figs. 18-47 of HMR No. 51). The choice of a single shape ratio for the entire region east of the 105th meridian simplifies the procedure for determining the hydrologically most critical pattern placement on a drainage, does not violate the data, and tends to be in the direction of the small-area patterns observed in major storms of record.

A recommended pattern is given in figure 5, drawn to a scale of 1 to 1,000,000. This pattern contains 14 isohyets (A through N), that we think would provide reasonable coverage of drainage areas up to about 3,000 mi^2. Since it would be cumbersome to include a pattern drawn to 1:1,000,000 scale with isohyets enclosing the largest suggested area, we have limited figure 5 to only 6,500 mi^2. All discussion of figure 5 implies a pattern of 19 isohyets extending from A to S and covers an area of 60,000-mi^2. It is necessary to provide patterns larger than 20,000 mi^2 (the limit of PMP given in HMR No. 51) in order to cover a narrow drainage with isohyets, particularly if the pattern and the drainage have different axial orientations, or if you want to consider non-basin centered placements. The 10-mi^2 isohyet is taken to be the same as point rainfall.

If it is desired to apply figure 5 to some other scale or to add larger isohyets to the pattern, and suitable templates are not available, table 8 aids the reproduction of figure 5 and gives the length in miles of the semi-minor and semi-major axes of an ellipse along with selected radials that enclose the suggested areas for a shape ratio of 2.5. For example, to obtain a 2,150-mi^2 ellipse, the minor axis is twice the value of 16.545 given in table 8, or 33.09 mi. The major axis is then 82.725 mi. The information in table 8 is sufficient to obtain isohyets that enclose areas for which HMR No. 51 is applicable.

The procedure in chapter 7 for determining isohyet values suggests that at times it may be necessary to consider isohyets supplementary to those specified in figure 5. To aid in construction of any additional isohyets, we provide the

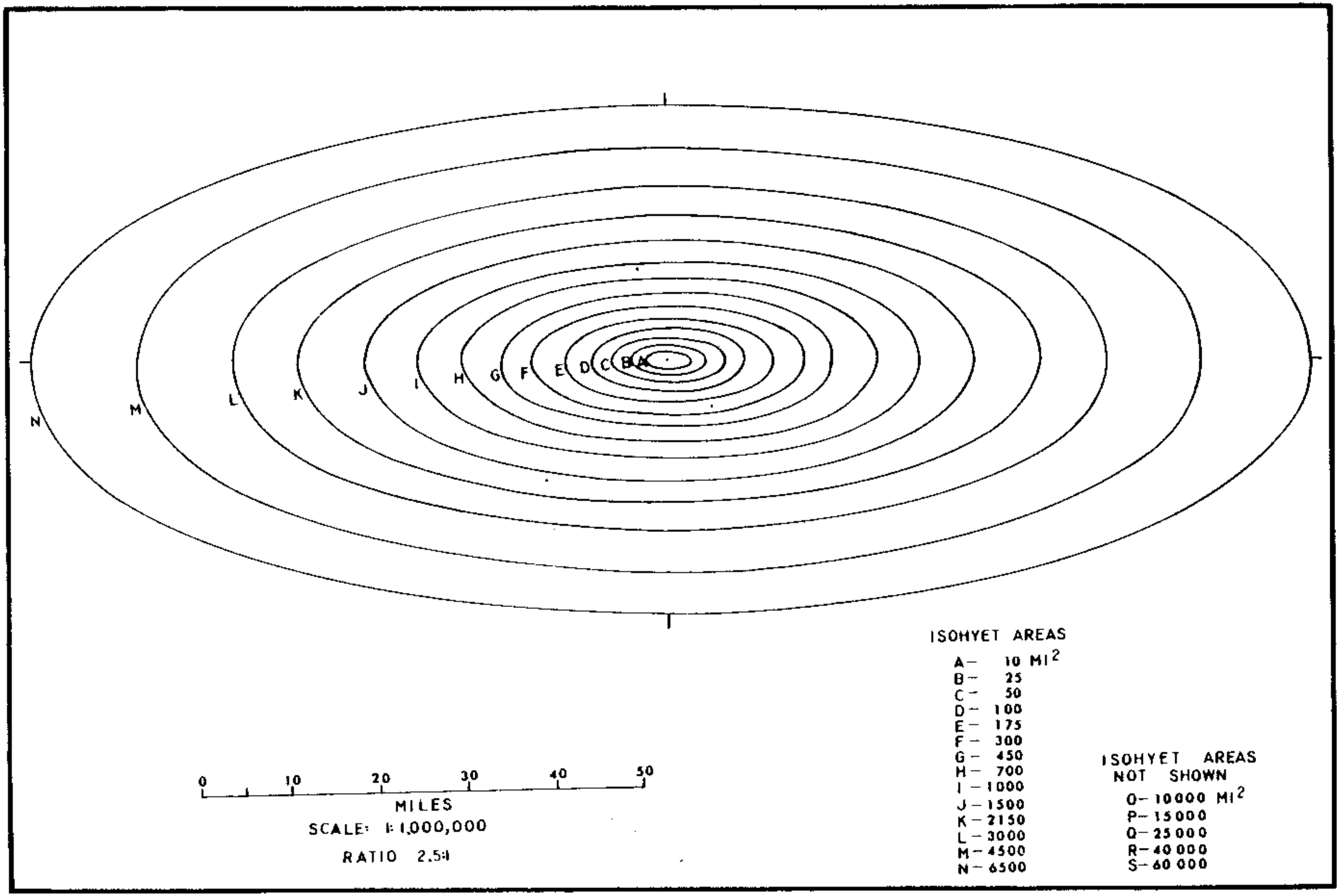


Figure 5.--Standard isohyetal pattern recommended for spatial distribution of PMP east of the 105th meridian (scale 1:1,000,000).

Table 8.--Axial distances (mi) for construction of an elliptical isohyetal pattern for standard isohyet areas with a 2.5 shape ratio (Complete four quadrants to obtain pattern)

Isohyet label	Standard isohyets enclosed area (mi^2)	Incremental area (mi^2)	Radial axis (deg.)* 0	15	30	45	60	90
A	10	10	2.820	2.426	1.854	1.481	1.269	1.128
B	25	15	4.460	3.836	2.933	2.342	2.007	1.784
C	50	25	6.308	5.426	4.148	3.313	2.839	2.523
D	100	50	8.920	7.672	5.866	4.685	4.014	3.568
E	175	75	11.801	10.150	7.758	6.198	5.310	4.720
F	300	125	15.451	13.289	10.160	8.115	6.953	6.180
G	450	150	18.924	16.276	12.444	9.939	8.516	7.569
H	700	250	23.602	20.301	15.521	12.397	10.622	9.441
I	1,000	300	28.209	24.263	18.550	14.816	12.965	11.284
J	1,500	500	34.549	29.717	22.720	18.146	15.549	13.820
K	2,150	650	41.363	35.577	27.200	21.725	18.614	16.545
L	3,000	850	48.860	42.026	32.130	25.662	21.989	19.544
M	4,500	1,500	59.841	51.470	39.351	31.430	26.930	23.936
N	6,500	2,000	71.920	61.860	47.294	37.774	32.366	28.768
O	10,000	3,500	89.206	76.728	58.661	46.853	40.145	35.682
P	15,000	5,000	109.225	93.973	71.846	57.383	49.168	43.702
Q	25,000	10,000	141.047	121.318	92.752	74.082	63.476	56.419
R	40,000	15,000	178.412	153.456	17.323	93.707	80.292	71.365
S	60,000	20,000	218.510	187.945	143.691	114.767	98.337	87.404

* 0° radial axis = semi-major axis
90° radial axis = semi-minor axis

following relations, where a is the semi-major axis, b is the semi-minor axis, and A is area of the ellipse.

For this study, $$a = 2.5b$$

For a specific area, A, $$b = \left(\frac{A}{2.5\pi}\right)^{1/2}$$

Radial equation of ellipse, $$r^2 = \frac{a^2 b^2}{a^2 \sin^2 0 + b^2 \cos^2 0}$$

where r = distance along a radial at an angle 0 to the major axis.

Although there is a slight tendency for circular patterns to occur for small area storms, we recommend the elliptical pattern in figure 5 for all drainage areas covered by HMR No. 51.

3.5 Application of Isohyetal Patterns

3.5.1 Drainage-centered patterns

This study recommends centering the isohyetal pattern (fig. 5) over a drainage to obtain the hydrologically most critical runoff volume. For many drainages that are not divided into sub-basins for analysis, the greatest peak flow will result from a placement of the isohyetal pattern that gives the greatest volume of rainfall within the drainage. The hydrologic trials to determine the greatest volume in the drainage discussed in section 5.3 may result in a placement that does not coincide with the geographic center of the drainage, particularly in irregularly shaped drainages. Centering of the isohyetal pattern as described here applies to the incremental volumes determined for each of the 6-hr PMP increments, each of which will be centered at the same point.

For some drainages, it may be hydrologically more critical to center the isohyetal pattern at some other location than that which yields the greatest volume. That is, recognizing that any location other than drainage-centered may result in less volume of rainfall in the drainage, it may nevertheless be possible to obtain a greater peak flow by placing the center of the isohyetal patterns nearer the drainage outlet. Characteristics of the particular drainage would be an important factor in considering these trial placements of isohyetal patterns. Should this secondary consideration for a nondrainage-centered pattern be used, the data in table 8 are believed sufficiently large in area covered to allow considerable flexibility in alternative placement of patterns, while still giving spatial distribution throughout the drainage. When it is determined that the zero isohyet occurs within the drainage, the area to use in hydrologic computations is that contained within the zero isohyet, and not the area of the entire drainage.

An additional benefit may be derived from the extent of coverage provided in table 8. This appears in the form of concurrent precipitation; i.e., if PMP is applied to one drainage, the extended pattern in many instances is sufficient to permit estimation of the precipitation that could occur on a neighboring drainage. This information is useful in evaluating effects from multiple drainages contributing to a hydrologic structure.

3.5.2 Adjustment to PMP for drainage shape

Whenever isohyetal patterns are applied to a drainage, there will be disagreement between the shape of the outermost isohyets and the shape of the drainage. Adjustment to drainage averaged PMP for this lack of congruency has been referred to in some past studies as a "fit factor" or a "basin shape" adjustment. In those studies, a comparison was made between the drainage-averaged PMP determined from planimetering isohyetal areas within the drainage and the total PMP (generally for 72 hr) derived from depth-area-duration data. It has generally been the case that the ratio of these depths, termed the fit factor, was then applied to each durational increment of the PMP.

Since we have established that there is a pattern shape assigned to each 6-hr increment, we can reasonably expect that there will be some reduction to the volume precipitation determined from the isohyetal pattern when the pattern is "fit" to an irregularly shaped drainage. Comparison of the drainage-averaged volume of precipitation and that from the depth-area curve derived from HMR 51 for a 6-hr period is indicative of the percentage reduction due to the drainage shape. The largest reduction occurs in the first 6-hr period and decreases with each succeeding 6-hr period.

3.5.3 Pattern applicable to PMP

When the isohyetal pattern in figure 5 is applied to a drainage, both drawn to the same scale, one might ask whether it is necessary to use all the isohyets given, since the outermost isohyet encloses 60,000 mi^2, well above the area size for which PMP is given. The answer to this question depends upon the shape of the drainage. It is only necessary to use as many of the isohyets of figure 5 as needed to cover the contributing portion of the drainage. If one has a perfectly elliptical drainage of 2,150 mi^2 with a shape ratio of 2.5, then it is only necessary to evaluate isohyets A through K in the pattern in figure 5. Since almost all drainages are highly irregular in shape, the K isohyet is unlikely to provide total coverage for a drainage of this size, and for an extremely long 2,150-mi^2 drainage, even though one is applying the 2,150-mi^2 PMP, it may be necessary to evaluate the M, N or larger isohyets.

At this point in our discussion, we note that figure 5 is applied only to the three greatest 6-hr increments of PMP (18-hr PMP). For the nine remaining 6-hr increments of PMP in the 3-day storm, we recommend a uniform distribution of PMP throughout the area of PMP. This means that for each of the three greatest increments, the magnitude of PMP is such that it is reasonable to expect it to be spatially distributed according to the isohyets in figure 5. However, the magnitudes of the increments of PMP decrease rapidly after the greatest 6-hr amount, and by the fourth 6-hr period are reduced to a level at which we assume they can be approximated by constant values over the PMP portion of the pattern for the fourth through 12th 6-hr periods.

Since most drainages have irregular shapes and as we have already discussed earlier in this section, the pattern shape in figure 5 will not fit when placed over the drainage. Therefore, there will be portions of the drainage that may for some unusually shaped drainages be uncovered by the pattern for a particular area size of PMP. (Chapter 5 discusses how to determine what area pattern to place on a drainage.) We are faced with the problem of what precipitation to expect outside the area of the PMP pattern. The solution lies in the concept of <u>residual precipitation</u>.

Residual precipitation is the precipitation that occurs outside the PMP area size pattern. For example, if we find the pattern area size that gives the maximum volume of PMP in the drainage is 2,150 mi^2, then for the 3 greatest 6-hr increments, apply figure 5, where the K isohyet encloses the PMP area. The isohyets inside and outside of K represent values that will give areal average depths somewhat less than PMP. In this example, the isohyets outside of K determine the residual precipitation. It should also be emphasized that residual precipitation is that outside the area of the PMP pattern, and not necessarily outside the drainage.

Now, for the fourth through 12th 6-hr periods we have assumed a constant value approximates the respective 6-hr increment of PMP through the area size of PMP. Therefore, for these increments, there would be no A through J isohyets in the patterns applied. But, there would remain isohyets outside the isohyet for the area size of the PMP (outside K in the above example), and thus there is a residual precipitation pattern assigned to each of the fourth through 12th 6-hr increments of PMP, in addition to the patterns for the three greatest 6-hr increments. (See discussion in section 5.2.5 and fig. 21.)

Although the concept of residual precipitation and its application and representation in isohyetal patterns is new, and perhaps confusing at this point, further discussion in chapter 5 and the examples in chapter 7 should be helpful.

4. ISOHYETAL ORIENTATION

4.1. Introduction

The subject of isohyetal orientation arises quite naturally from discussion of placing isohyetal patterns over a drainage, since the orientation of a PMP pattern and that of the drainage over which it is placed may be entirely different. Guidance is needed on how well these orientations match for the PMP storm. It is assumed, though perhaps not always true, that the greatest volume of rainfall within a drainage results when the isohyetal pattern and the drainage are similarly oriented.

An objective of this section, therefore, is to determine whether there are meteorological restrictions or preferences for certain orientations. We are also interested in determining if there are any regional variations or constraints on orientations due to terrain or other factors.

As in the previous chapter, we rely on major observed storm rainfalls and apply the results to adjust the isohyetal orientation of the 6-hr PMP increments. (See section 5.2.1.)

Since 6-hr incremental isohyetal patterns are available only for a very few storms, we assume that the orientation of isohyets for the 6-hr incremental patterns of rainfall is the same as that for the total storm. Limited support for this assumption is found in the few incremental isohyetal patterns given in a study of Mississippi River basin storms by Lott and Myers (1956). For 10 of the 18 storms studied by Lott and Myers, 6-hr isohyetal patterns were determined. The orientations of the 6-hr isohyetal increments for these 10 storms vary from the total-storm orientations by no more than 40°.

4.2 Data

The sample of isohyetal patterns from the 53 major storms in table 1 were considered for the study of isohyetal orientations.

4.2.1 Average orientations

In this chapter, reference is sometimes made to the average of several orientations. It is believed important to remark here on how these averages were obtained, because averages of angular measure do not follow that of simple arithmetic averages. First, recognizing that every orientation line (or axis) is

Problem: *Obtain an average of three orientation lines given below. If the lines are designated as #1 = 020° or 200°, #2 = 150° or 330°, and #3 = 165° or 345°, then if we average 020°, 150° and 165°, we get 112°, which is seen to represent a false average.*

Solution: *Choose values to average from ends of the lines (quadrants) that give the minimum range. Here the range of 200° minus 150°, or 380° minus 330°, is the minimum (50° range). Thus, the representative average is 172°, or 352° respectively.*

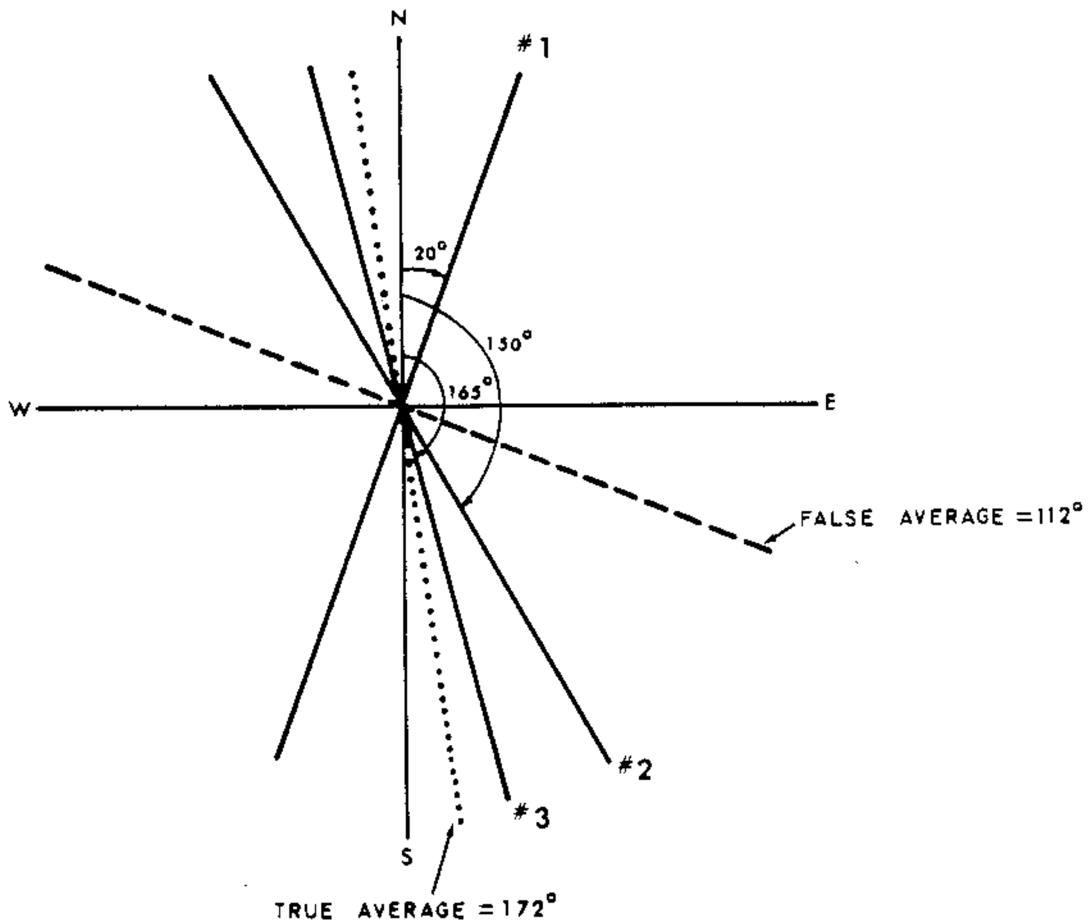


Figure 6.—Schematic example of problem in averaging isohyetal orientations.

2-valued, we obtain different averages relative to which value is chosen to represent a particular orientation. Therefore, a rule must be developed, when averaging such values, on which of the 2 values to use so that everyone obtains a comparable and representative result. The rule we applied was to use those values that would give a minimum range for all the values to be averaged. This procedure will be illustrated by the following example. Average the three orientation lines in figure 6 (#1 is 020° - 200°, #2 is 150° - 330°, and #3 is 165° - 345°). (Three orientations are considered here only to keep the problem simple; the procedure is the same regardless of the number of orientations to be averaged). If one chose to average the three smallest values (reading from north) of 20°, 150° and 165°, the result would be 112° given by the dashed line in figure 6. This is an unrepresentative average when compared to the three solid lines in this figure. We say the range of those 3 values is 145° (165° minus 020°). However, following the rule to obtain a minimum range, consider the three values of 150°, 165° and 200° (representing the same three orientations, but reading the other end of the 020° - 200° line). We get a range of 50° (i.e., 200° minus 150°), and similarly a 50° range is obtained for the set of other ends to these same 3 lines (380° minus 330°). Since 50° is the least difference we can obtain from any set of directions, for these 3 particular lines, the correct values to average are either 150°, 165° and 200° or, 020° + 360°, 330° and 345°, for which the average orientation is 172° or 352°, respectively shown by the dotted line in figure 6.

4.2.2 Orientation notation

Although each orientation line is 2-valued, we have chosen to represent each orientation by only one value in the remainder of this chapter. This convention greatly simplifies the notation assigned to graphs and tables. In selecting the one value to identify each orientation, we could have arbitrarily chosen values between 0° and 180° (from north). However, this choice is but one of many possible choices, each covering a range of 180°, and we adopted the 180° sector between 135° and 315° for this study. This particular choice resulted from considerations of meteorological bases for the observed pattern orientations, which are related to the moisture bearing inflow winds. Wind is commonly reported as the direction the wind is blowing from. Atmospheric winds during periods of maximum moisture in the United States east of the 105th meridian are predominantly in the quadrant from the south to west. In addition, analysis for our storm sample indicated that most rainfall patterns had orientations that varied about a southwest-northeast axis.

4.3 Method of Analysis

An isohyetal orientation was determined for each of the major total-storm rainfall patterns in table 1. We prescribed that the orientation line for each pattern pass through the location of maximum reported point rainfall. Some complex isohyetal patterns necessitated subjective judgments on the orientation, because of multiple possible orientations or incomplete total-storm patterns. The latter was particularly the case along coastal zones. Direction of the orientation in each rainfall pattern was read to the nearest 5 degrees. Orientations determined for the 53 storms, listed in table 1, have been plotted at their respective locations in figure 7.

4.4 Analysis

The amount of variation in orientations given in table 1 and figure 7 gave rise to the question, whether it was possible to generalize these orientations into a consistent pattern over the entire study region.

4.4.1 Regional variation

The same six subregions used to study shape ratios were used to determine regionally averaged orientations. Averages of the orientation for the major storms in each subregion are given in table 9. The range of orientations for storms considered in each subregion is also indicated.

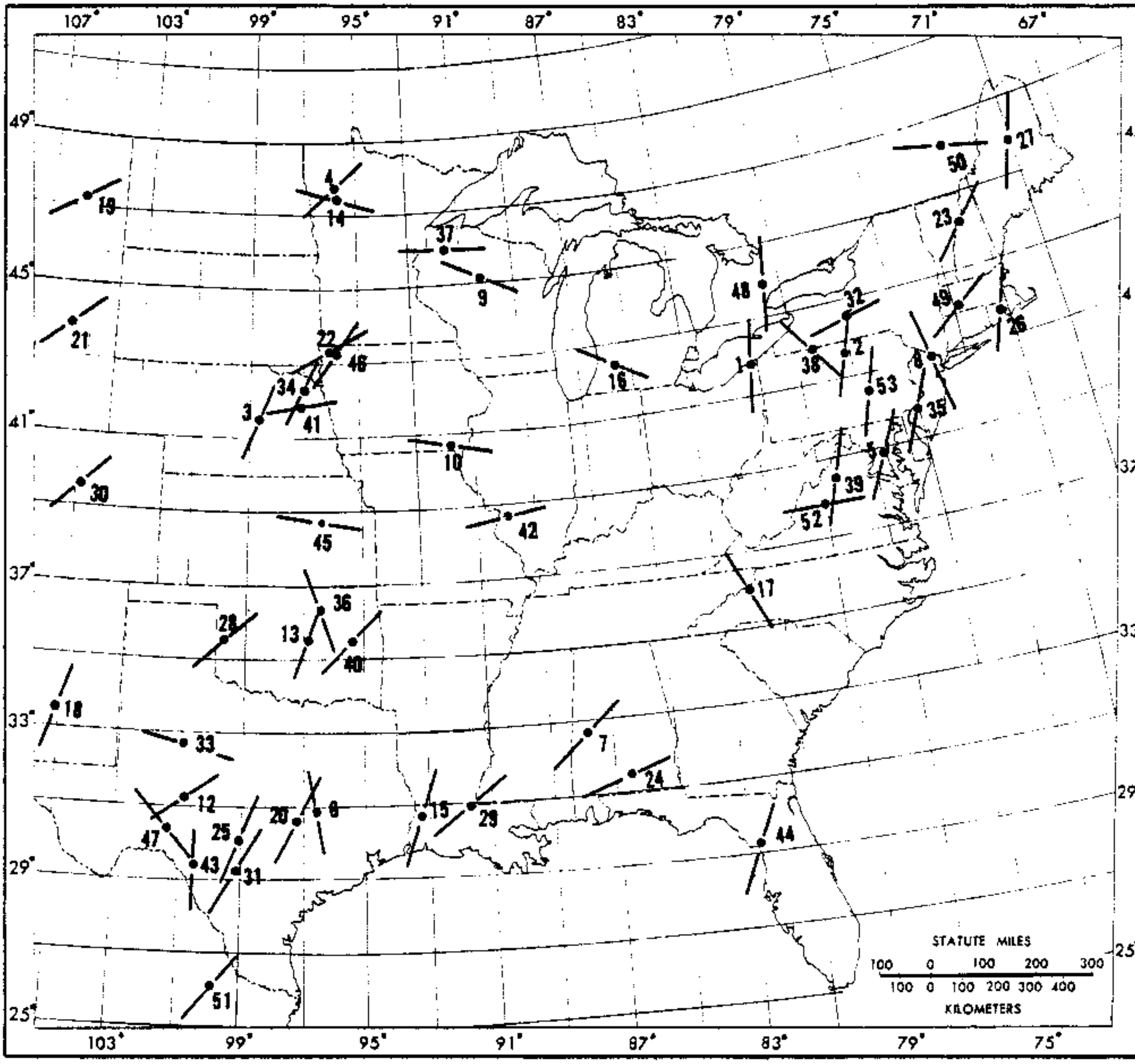


Figure 7.—Location and orientation of precipitation pattern for 53 major storms listed in HMR No. 51. Identification numbers refer to table 1.

Table 9.—Averages of isohyetal orientations for major storms within selected subregions of the eastern United States (storms contained in appendix of HMR No. 51)

Subregion	No. of Storms	Average orientation (deg)	Range in orientations (deg)
Atlantic Coast	5	202	170 to 230
Appalachians	5	194	145 to 270
Gulf Coast	9	214	170 to 290
Central Plains	6	235	160 to 285
North Plains	4	270	230 to 295
Rocky Mt. Slopes	4	224	200 to 240

Although the results in table 9 represent a small sample, we feel that a tendency is shown for some regional variation among these subregions. Support for this conclusion was based in part on results from a similar analysis of the larger sample of storms discussed in the appendix and summarized in table 10. We subdivided the Appalachians into storms that occurred east and west of the ridgeline. By so doing, the results for the Appalachians suggest that orientations in this region closely agree with the subregions to the east (Atlantic Coast) and to the west (Central Plains). This distinction does not appear in the results for table 9, because none of the storms considered occurred to the west of the ridgeline. A general picture of the regional variation of isohyetal orientation is obtained from these two samples: orientations are southwesterly east of the Appalachians, along the Gulf Coast, and along the east slopes of the Rocky Mountains, but become more westerly in the Plains States. Meteorological bases for those observed orientations will be discussed in section 4.5.

Table 10.—Average of isohyetal orientation for the large sample of storms within selected subregions in the eastern United States

Subregion	No. of storms	Average orientation (deg.)	Range in orientations (deg.)
Atlantic coast	26	204	140 to 305
Appalachians (East)	17	204	155 to 240
Appalachians (West)	6	278	240 to 305
Gulf Coast	50	235	140 to 300
Central Plains	43	256	195 to 300
North Plains	25	257	185 to 310
Rocky Mt. Slopes	16	214	170 to 290

4.4.2 Generalized isohyetal orientations

Assuming from tables 9 and 10 that there is a regional variation in isohyetal orientations of major storms, we want to determine the regional variation that represents PMP. It would be desirable to generalize orientations by a continuous analysis across the entire study region.

As a first approach we plotted the subregion averages from table 9 at their respective locations, centered to represent the centroids of the storms averaged. From this basis, a rough pattern was drawn to show regional variation (not shown here). It was felt that although a general pattern could be obtained in this manner, drawing to five data points for so large a region was less than desirable.

A decision was made to consider a number of major storms distributed throughout the region and develop the generalized pattern from their orientations. Storms were selected from table 1 according to the following conditions:

1. No other major storm in table 1 occurred within a radius of 100 miles of the storm chosen. When two or more storms were within 100 miles of one another, only the storm with the larger 24-hr 1,000-mi^2 depth was considered.

2. No storm was selected whose total storm duration was less than 24 hr, as they were believed to represent local storms for which almost any orientation is believed possible.

With this guidance, 25 storms (roughly one-half the storms in table 1) were selected. In addition, to the 25 major storms from table 1, six storms were selected from "Storm Rainfall" (U.S. Army Corps of Engineers 1945-   ) to fill in portions of the region not represented by storms in table 1. These storms also met the selection criteria noted above.

The 31 storms were plotted at their respective locations as shown in figure 8. Through considerable trials, a generalized pattern was drawn which attempted to match as many of the storm orientations as possible and yet maintain some internal consistency regarding gradients and smoothness. Also shown in figure 8 is the result of this analysis.

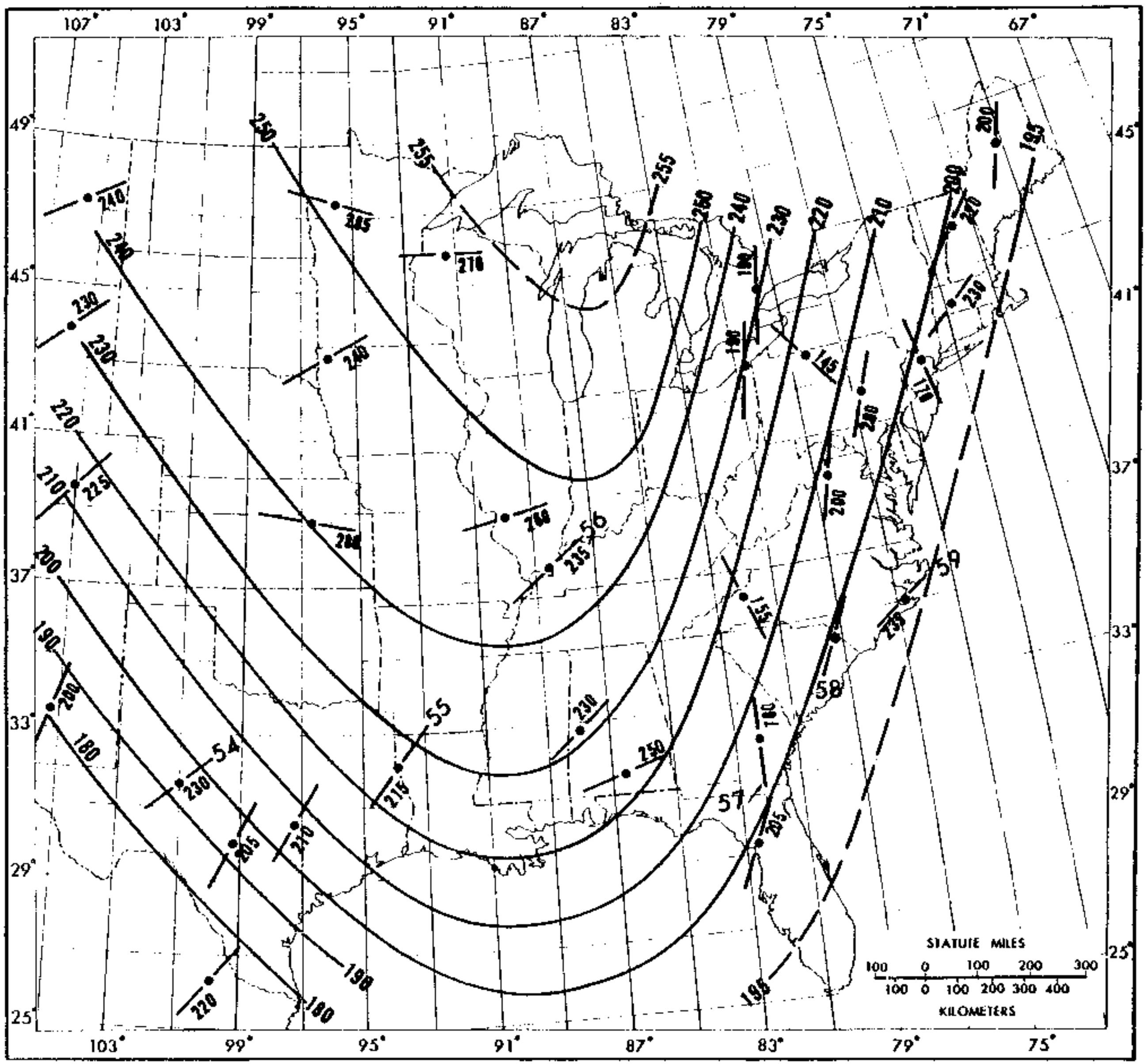
In making the analysis shown in this figure, we attempted to control the variation from observed orientation whenever possible. Table 11 lists the 31 differences. It is apparent that some large variations occur, e.g., 72° at Smethport, Pennsylvania. For the most part, variations are considerably less, as summarized by 10° categories in table 12. Two-thirds of the analysed orientations are within 30° of the observed orientations, while nearly 94% are within 50°.

Although there are some portions of the region (e.g., eastern Great Lakes) that show rather large variation from the analysis, a decision was made not to complicate the analysis further by creating regional anomalies. Therefore, the analysis shown in figure 8 was adopted to represent the pattern of orientations for our data, and we further assumed that this pattern applied to the most favorable conditions for PMP. For drainages that lie outside the region covered by the analysis (for example in northern Michigan), use the orientation of the nearest isopleth.

4.4.3 Variation of PMP with pattern orientation applied to drainage

In application of PMP to specific drainage, figure 8 is used to determine the orientation of the isohyetal pattern most likely to be conducive to a PMP type event. It is unrealistic to expect that figure 8 is without error and that PMP at any location is restricted to only one orientation. For these reasons we recognize that it is more reasonable that PMP occur through a range of orientations centered on the value read from figure 8. Following this line of reasoning, we also expect that for precipitation orientations that do not fall within the optimum range, the magnitude of PMP would be somewhat less.

4.4.3.1 Range of full PMP. The range of full PMP (100% PMP) is that range of orientations, centered on the value read from figure 8, for which there is no reduction to the amounts read from HMR No. 51 for orientation. Our concept of PMP is that the conditions resulting in a PMP-type event are somewhat restricted, and we believe that the range of full PMP should also be limited. However, to gain support for this limitation, we again referred to our sample of major storms and, from the summary of orientations in table 12, we chose a range of ±40° (representing about 85 percent of the variation in our sample) to assign to PMP. Therefore, whenever the pattern best fitted to the drainage for which PMP is being determined has an orientation that falls within 40° of the orientation obtained for that location (from fig. 8), full PMP is used.



SUPPLEMENTAL STORMS

54. BROOME, TX
55. LOGANSPORT, LA
56. GOLCONDA, IL
57. GLENVILLE, GA
58. DARLINGTON, SC
59. BEAUFORT, NC

Figure 8.--Analysis of isohyetal orientations for selected major storms adopted as recommended orientation for PMP within ± 40°. Addition of 6 major storms not in figure 7 have been identified numerically above station locations and in the margin.

Table 11.—Major storm orientations relative to generalized analysis including summary information

Storm index no. from table 1	Name	24-hr 1000-mi^2 depth (in.)	Observed orientation (deg.)	Orientation from analysis (deg.)	Differences
1	Jefferson, OH	11.0	190	230	+40
7	Eutaw, AL	11.3	230	231	+ 1
8	Paterson, NJ	10.9	170	199	+29
14	Beaulieu, MN	10.0	285	251	-34
17	Altapass, NC	15.0	155	218	+63
18	Meek, NM	5.0	200	182	-18
19	Springbrook, MT	11.3	240	241	+ 1
20	Thrall, TX	24.3	210	205	- 5
21	Savageton, WY	6.6	230	230	0
22	Boyden, IA	10.6	240	246	+ 6
23	Kinsman Notch, NH	7.8	220	200	-20
24	Elba, AL	16.1	250	224	-26
25	St. Fish Htchy, TX	19.0	205	194	-11
27	Ripogenus Dam, ME	7.7	200	198	- 2
30	Hale, CO	7.2	225	213	-12
37	Hayward, WI	9.1	270	253	-17
38	Smethport, PA	13.3	145	217	+72
39	Big Meadows, VA	10.3	200	209	+ 9
42	Collinsville, IL	9.0	260	247	-13
44	Yankeetown, FL	30.2	205	200	- 5
45	Council Grove, KS	6.6	280	240	-40
48	Bolton, Ont., Can.	6.4	190	230	+40
49	Westfield, MA	12.4	230	198	-32
51	Sombreretillo, Mex.	11.9	220	170	-50
53	Zerbe, PA	12.3	200	207	+ 7
Supplementary storms					
54	Broome, TX	13.8	230	195	-35
55	Logansport, LA	14.8	215	225	+10
56	Golconda, IL	7.4	235	244	+ 9
57	Glenville, GA	13.1	180	205	+25
58	Darlington, SC	10.8	205	199	- 6
59	Beaufort, NC	11.5	235	196	-39

4.4.3.2 Reduction to PMP for orientation outside of range. We have stated that for orientations that differ from the central value from figure 8 by more than 40°, less than PMP-type conditions are likely, and therefore we feel a reduction can be made to the PMP determined from HMR No. 51. It is also reasonable to expect that as the difference between PMP orientation and orientation of the pattern on the drainage increases, the reduction applied to PMP should increase.

Table 12.—Frequency of various difference categories between observed and preferred orientations

Categ. (deg.)	-50 to -41	-40 to -31	-30 to -21	-20 to -11	-10 to -1	0 to 9	10 to 19
Freq.	1	5	1	6	4	7	1
%	3	16	3	19	13	23	3

Categ. (deg.)	20 to 29	30 to 39	40 to 49	50 to 59	60 to 69	70 to 79	Total
Freq.	2	-	2	-	1	1	31
%	6	-	6	-	3	3	98

Range	Frequency	Cum. %
±10°	11	35.5
±20°	18	58.1
±30°	21	67.7
±40°	26	83.9
±50°	29	93.5
±60°	29	93.5
±70°	30	96.8
±80°	31	100.0

Because we anticipated there could be a regional variation, we considered the subregions in figure 4. Our sample in table 1 of major storms within these subregions is too small to be useful, and we relied on the increased sample described in the appendix. Within each subregion, storms were ranked according to magnitude of 72-hr 20,000-mi^2 depth, and then converted to percent of the maximum depth occurring in each region. We plotted the percent of maximum rainfall vs. orientation for each storm by geographic region. An enveloping curve drawn on these graphs provided guidance on the range of orientations that should be permitted without reduction and on the appropriate reduction for greater variations. The data for the Gulf Coast region are shown in figure 9, as an example of these plots.

In figure 9, the Hearne, Texas (6/27-7/1/1899) storm gave the maximum depth, and the Elba, Alabama (3/11-16/1929) storm was the second greatest at about 80 percent of the Hearne depth. We remind the reader that since orientation is a form of circular measure, the left-hand end of the scale in figure 9 is identical with the right-hand end of the scale.

Considering each of the subregional distributions, of which figure 9 is an example, we developed a model based essentially on envelopment of subordinate depth storms. The model shows that 100 percent of PMP applies within ± 40° of the central value as indicated in section 4.4.3.1. Maximum reduction to PMP is limited to 15 percent applicable to orientation differences of ± 65° or more. This model is given in figure 10, in which the adjustment factor (100% minus the percentage reduction) to PMP is read from the right-hand axis for differences of orientation from the central value obtained from figure 8 (represented by the 0 value on the left of the model).

4.4.3.3 Variation due to area size. It appears reasonable that no reduction should be applied to storms on the scale of a single thunderstorm cell (or